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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 6th Interim	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Cyclic Fatigue Behaviour of Adhesive Joints		5. TYPE OF REPORT & PERIOD COVERED 6th Interim: December 1994 - June 1995
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A.J. Kinloch T. Toh		8. CONTRACT OR GRANT NUMBER(s) DAJA 45-93-C-0008
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mechanical Engineering Dept., Imperial College, Exhibition Road, London, SW7 2BX		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS United States Army, European Research Office		12. REPORT DATE 12th June 1995
		13. NUMBER OF PAGES 6
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) -		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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DTIC ELECTE JUL 14 1995 S D B

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

-

18. SUPPLEMENTARY NOTES

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DISTRIBUTION STATEMENT A

Approved for public release; Distribution Unlimited

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adhesives, Cyclic Testing, Durability, Fracture Energy

DTIC QUALITY INSPECTED 5

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In the last six months we have:
(a) Concentrated our efforts on the fatigue failure of carbon-fibre PEEK/AF163 lap joints, and in particular we have started to predict the life time of single-lap joints under cyclic fatigue loading. Further, we have been successful in measuring the rate of crack growth in lap joints during fatigue fracture using ultrasonic scanning.
(b) Preliminary test data on the static fracture of glass-fibre reinforced poly(phenylene sulphide) (PPS)/AF163 joints have also been studied.

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1.INTRODUCTION

The presence of cyclic stresses presents the most severe service condition, and one that has posed a number of problems for the design engineer. In recent times, a concerted research effort has been directed at understanding the mechanisms of fatigue failure, and in particular how crack propagation is influenced by fatigue cycling occurring in the presence of a hot/wet environment. A major difficulty has always been the extrapolation of laboratory experimental data to predict the behaviour of real structures.

The present research program evolved as a result of an attempt to understand the fatigue failure of a range of structural adhesive joints used in military applications. The work to-date has investigated both the static and cyclic stress failure of a structural adhesive AF163 (supplied by '3M', USA) bonded to aluminium-alloy and carbon fibre reinforced poly(ether-ether ketone) (PEEK) substrates, using various pre-treatments, in both dry and wet environments. Recently we have extended this work to include glass-fibre poly (phenylene sulphide) as a substrate material of interest.

2.OVERALL PROGRESS

In the last six months we have:

(a) Concentrated our efforts on the fatigue failure of carbon-fibre PEEK/AF163 lap joints, and in particular we have started to predict the life time of single-lap joints under cyclic fatigue loading. The analysis is based on data obtained from double-cantilever-beam (DCB) fracture mechanics tests.

(b) Further, we have been successful in measuring the rate of crack growth in lap joints during fatigue fracture using ultrasonic scanning.

(c) Preliminary test data on the static fracture of glass-fibre reinforced poly(phenylene sulphide) (PPS)/AF163 joints have also been studied.

(d) A comparison has been made in computing the critical strain energy release rate G_c for the glass-fibre PPS/AF163 joints based on the compliance method, beam theory and corrected beam theory. The last method accounts for large non-linear deflections and the associated crack root rotations along with the necessary corrections for the increase in stiffness introduced by the presence of end blocks [1].

3.THEORETICAL BACKGROUND

A single lap joint loaded in tension normally fails due to transverse tensile or cleavage stresses which act at right angles to the direction of the applied load. The maximum value of the peel stress at the end of the overlap in a single lap joint was determined by Hart -Smith [2] as:

$$\sigma_{max} = M_e \left(\frac{E_a}{2\,t_a X}\right)^{1/2} \qquad [1]$$

where:

E_a = modulus of the adhesive
t_a = thickness of the adhesive layer

and the value of the bending stiffness X and bending moment per unit width M_e are obtained from the equations below:

$$X = \frac{E_s h^3}{12(1-\mu^2)} \qquad [2]$$

where:

E_s = modulus of the substrate
h = thickness of the substrate
μ = Poisson's ratio of the substrate

and:

$$M_e = 0.5 \, K \, T \, (h+t_a) \qquad [3]$$

where:

T = applied tensile load per unit width

and K is the bending moment factor given by :

$$K = \frac{1}{1 + \varepsilon c} \qquad [4]$$

where c = half the bonded overlap in the direction of the applied load, and:

$$e = \left(\frac{T}{X}\right)^{1/2} \qquad [5]$$

From the above we may obtain:

$$M_e = \frac{T\,(h + t_a)}{2\,(1 + \varepsilon c)} \qquad [6]$$

Now, Williams [3] proposed a very powerful method using the simple beam theory to estimate the mode I fracture energy, G_{max}, from a knowledge of the bending moment at the crack tip of cracked laminates made from thin sheets. This beam theory analysis may also be applied to composite laminate and to bonded composite joints. The Williams equation can be used to estimate the fracture energy in a single lap joint (SLJ) due to the presence of bending moments at the end of the overlap, and gives:

$$G_{max} = \frac{12\,M^2}{B^2 E_s h^3} \qquad [7]$$

Combining the above equations, we have:

$$G_{max} = \frac{12}{E_e h^3} \left(\frac{T\,(h + t_a)}{2}\right)^2 \left(\frac{1}{(1 + \varepsilon c)^2}\right) \qquad [8]$$

In the next period of work we will use these equations, which relate the critical strain energy release rate G_c in the single-lap joint to the maximum load per unit width applied to the lap joint, in order to predict the fatigue life of the lap joint. Since, from the DCB fracture mechanics tests, we can experimentally measure the value of G_c as a function of the fatigue crack growth rate per cycle and we can also determine the minimum, or threshold, value of G_c, below which no fatigue crack growth will be observed.

4. EXPERIMENTAL

4.1 Carbon-fibre PEEK/AF163 Single-Lap Joints

The carbon-fibre/PEEK composite laminates were made from the prepregs stacked with the ply direction at 0^o. The laminates consists of a matrix of thermoplastic polymer, poly(ether-ether ketone) (PEEK) reinforced with 61% by volume of unidirectional carbon fibres. A total of 24 plies were used to obtain a final substrate thickness of about 3mm for the single-lap joints (SLJ). The laminates were compression moulded in a hot press at 380^oC for 5 minutes at a pressure of 200psi followed by post consolidation cooling at a pressure of 300psi. Rectangular strips of 25.4mm x 188mm were cut from these laminates and bonded using the 'AF163 film adhesive', an overlap length of 12.7 mm was used. Prior to bonding the PEEK substrates were grit blasted, solvent wiped and then corona treated. It was established that the PEEK composite requires a corona energy level of $29J/mm^2$ to achieve cohesive failure in the adhesive layer. The cure schedule for the adhesive is as described in previous reports [4]. A typical SLJ geometry is shown below.

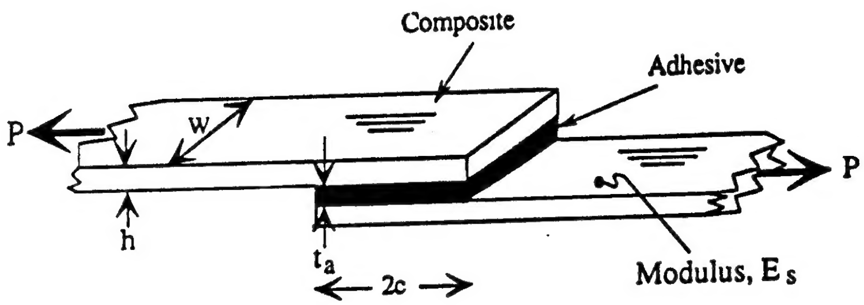

Fig. 1 SLJ Geometry

Initially, static tests were conducted in dry air at 25^oC and 55%RH and at a cross-head velocity of 1mm/min to establish the maximum static load P_c and the value of G_c. The fatigue tests were conducted at a maximum of 80% of the static load at a loading frequency of 5Hz and a load ratio of 0.5, in load control. During the tests, the corresponding maximum load applied on each cycle and the number of cycles to failure were recorded.

4.2 Glass-fibre PPS/AF163 Double-Cantilever-Beam Joints

The glass-fibre PPS material was cut into strips about 20mm x 140mm x 6mm and was (a) either abraded and solvent wiped or (b) plasma treated in an oxygen plasma. The adhesive AF163 was used to bond together two composite strips to form a DCB joint, which contained an initial debond, as previously reported [4]. The static tests were conducted at a rate of 1mm/min, and in all the joints the failure was via interlaminar failure of the glass-fibre PPS composite. Hence, there was no observable effect of

surface pre-treatment, since even a simple abrasion/solvent cleaning treatment was sufficient to attain adequate adhesion for failure to occur in the composite substrate.

5.RESULTS AND DISCUSSION

5.1 Carbon-fibre PEEK/AF163 Single-Lap Joints

The load per unit width, T_{max}, versus the number, N_f, of cycles to failure (i.e the S-N curve) obtained for SLJ's of PEEK-Composite/AF163 is shown in Fig.2. As would be expected, the number of cycles to failure increases as T_{max} decreases. The theory we have been developing, and outlined above, is currently being applied to see whether we can predict the long-term lap-joint fatigue results, shown in Fig. 2, from the short-term fracture mechanics results which we have reported previously [5].

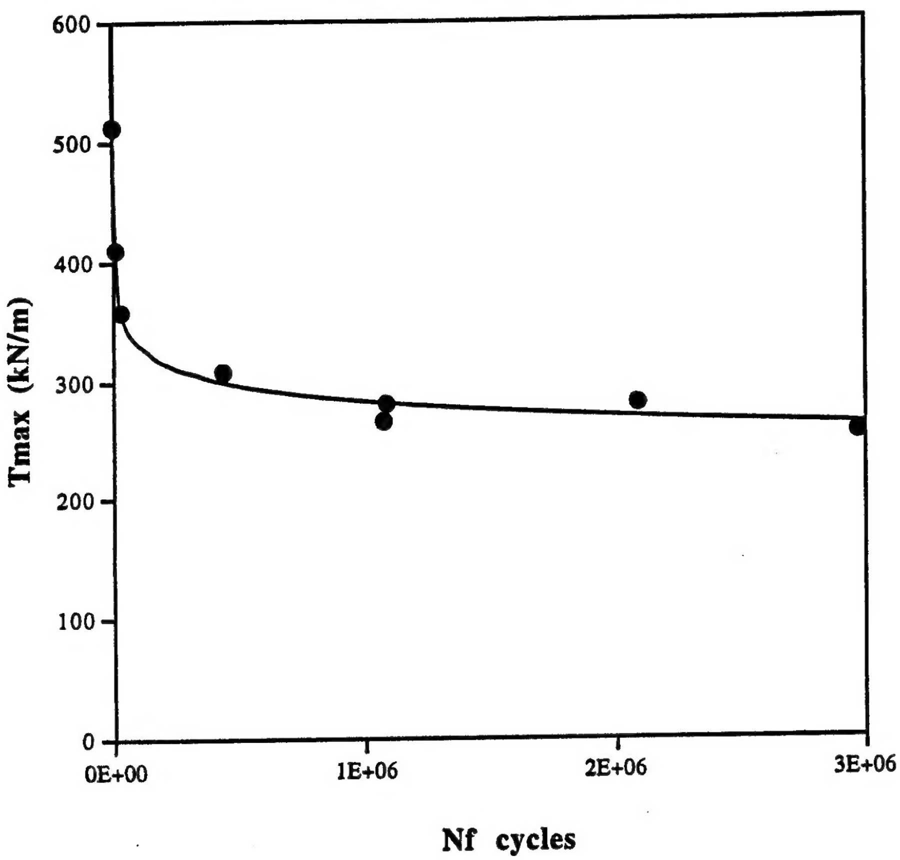

Fig. 2 Fatigue Results for Lap Joint Tests (PEEK composite/AF163 joints)

Further, we have attempted to elucidate the way in which cracks propagate in these joints by stopping a fatigue test on a single-lap joint prior to failure, and subsequently ultrasound scanning the test joint at two intervals. The first scan was conducted after the SLJ had been fatigue-cycled for 1.5million cycles, and the second scan was taken after 2million cycles. The results of these tests are shown in Fig.3. As has been suggested by Kinloch & Osiyemi [5], crack growth originates from either end of the overlap changing the effective overlap length.

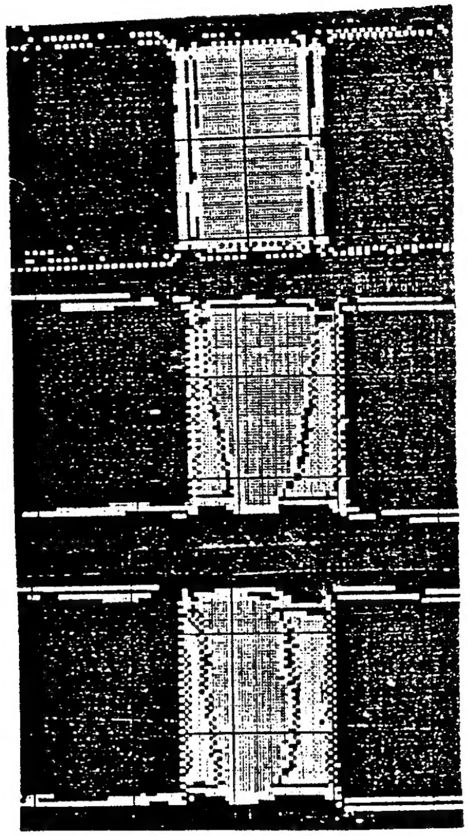

Fig.3 Ultrasound Scans of a PEEK/AF163 single-lap joint. (a) as made; (b) after 1.5million fatigue cycles; (c) after 2million fatigue cycles.

5.2 Preliminary Static Fracture Data on Glass-Fibre PPS/AF163 DCB Joints

In all these joints the failure was interlaminar in the fibre-composite substrate and the crack propagated in a steady, stable, manner. The fracture energy, G_C, was computed based on the corrected load, displacement and the compliance methods. A detailed explanation of these methods is beyond the scope of this report and the reader is referred to reference [6] for a more complete account. Tests were conducted in triplicate and a rising 'R-curve' was observed in all three tests, i.e. the fracture energy, G_C, increased as the crack propagated in an interlaminar manner through the joint. A plot of G_C versus crack length, a, is shown in Fig.4. (The G_C values presented in these plots were calculated from an analyses based on the corrected-beam theory.)

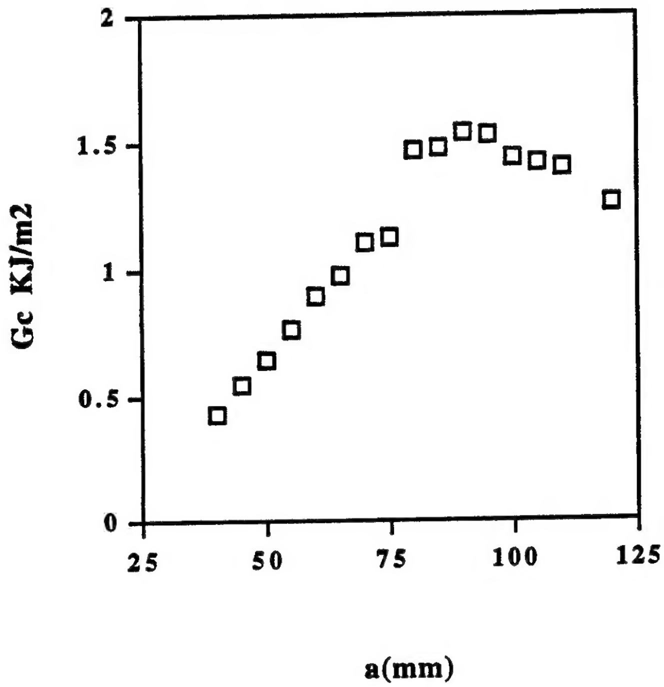

Fig.5 The variation of fracture energy, G_c, with the crack length, a, for glass-fibre PPS/AF163 DCB joints.

6.FUTURE WORK

1. The measurement of the threshold fracture energy, G_{th}, of a carbon-fibre PEEK/AF163 DCB joint when fatigue tested will be undertaken. This is a necessary requirement in order to complete the life-time prediction studies.

2. Further investigations of the glass-fibre-PPS/AF163 system will be undertaken; for example, testing more single-lap joints to see whether interlaminar failure still occurs, even when very long overlap lengths are used.

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